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Global natural history infrastructure requires international solidarity, support, and investment in local capacity

Bazartseren Boldgiv[a], Ariuntsetseg Lkhagva[a], Scott Edwards[b,c], Nils C. Stenseth[d], Jamsranjav Bayarsaikhan[e,f], Dondog Altangerel[g], Dorj Usukhjargal[a], Badamgarav Dovchin[h], Sundev Gombobaatar[a], Nyamsuren Batsaikhan[a], Christina Warinner[i,j], Isaac Hart[k,l], Kurt Galbreath[m], Stephen E. Greiman[n], Jason Malaney[o], James D. Murdoch[p], Bryan McLean[q], Sharon N. DeWitte[r], Erin Manzitto-Tripp[s,t], Karen Chin[s], Talia S. Karim[s], Carl Simpson[s,u], Nancy J. Stevens[s,v], Jonathan L. Dunnum[w], Joseph A. Cook[w], and William Timothy Treal Taylor[s,v,1]

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Amid global challenges like climate change, extinctions, and disease epidemics, science and society require nuanced, international solutions that are grounded in robust, interdisciplinary perspectives and datasets that span deep time. Natural history collections, from modern biological specimens to the archaeological and fossil records, are crucial tools for understanding cultural and biological processes that shape our modern world. At the same time, natural history collections in low and middle-income countries are at-risk and underresourced, imperiling efforts to build the infrastructure and scientific capacity necessary to tackle critical challenges. The case of Mongolia exemplifies the unique challenges of preserving natural history collections in a country with limited financial resources under the thumb of scientific colonialism. Specifically, the lack of biorepository infrastructure throughout Mongolia stymies efforts to study or respond to large-scale environmental changes of the modern era. Investment in museum capacity and training to develop locally-accessible collections that characterize natural communities over time and space must be a key priority for a future where understanding climate scenarios, predicting, and responding to zoonotic disease, making informed conservation choices, or adapting to agricultural challenges, will be all but impossible without relevant and accessible collections.

collections | colonialism | infrastructure | natural history | Mongolia

As countries around the world navigate the effects of rapid and severe climate change, biodiversity declines, and recurring wildlife and human epidemics, these global challenges have also underscored our collective interdependence as a scientific community. Complex global problems require nuanced, international solutions that are grounded in robust, interdisciplinary perspectives. Among the most important tools for addressing the challenges of the 21st century are natural history collections, which curate critical archaeological, paleobiological, and biological resources necessary to anticipate and respond effectively to global change. Natural history collections play crucial roles in understanding the distributions of biodiversity, past and present (1, 2); exploring taxonomy, phylogeny, and conservation (3); assessing causes of biodiversity decline and loss (4); informing endangered species recovery (5); tracking wildlife reservoirs of infectious diseases to help anticipate and mitigate future outbreaks (6–8); identifying and tracking how environmental pollutants circulate (9, 10); and reconstructing sustainable practices in animal husbandry and pasture management (11). As these challenges are poised to accelerate in the 21st century, developing effective responses require datasets that are locally relevant to the world's diverse landscapes and ecosystems, and can trace cultural and biological change across different timescales.

Global Threats to Natural History Collections

Globally, natural history collections are at-risk, understaffed, and underresourced, undermining efforts to build both the infrastructure and scientific capacity necessary to tackle critical challenges. Even at major western institutions, natural history collections and associated expertise face a perpetual struggle for funding, administrative support, facilities upkeep, and

Author affiliations: [a]Department of Biology, National University of Mongolia, Ulaanbaatar 14201, Mongolia; [b]Museum of Comparative Zoology, Harvard University, Cambridge, MA 02138; [c]Department of Organismic and Evolutionary Biology, Harvard University, Cambridge, MA 02138; [d]Centre for Ecological and Evolutionary Synthesis, Department of Biosciences, Faculty of Mathematics and Natural Sciences, University of Oslo, Oslo 0316, Norway; [e]Institute of Archaeology, Mongolian Academy of Sciences, Ulaanbaatar 13330, Mongolia; [f]Max Planck Institute for Geoanthropology, Jena 07745, Germany; [g]Natural History Museum of Mongolia, Ulaanbaatar 15141, Mongolia; [h]Round River Conservation Studies, Bozeman, MT 59715; [i]Department of Anthropology, Harvard University, Cambridge, MA 02138; [j]Department of Archaeogenetics, Max Planck Institute for Evolutionary Anthropology, Leipzig 04103, Germany; [k]American Center for Mongolian Studies, Sukhbaatar District, Ulaanbaatar 15160, Mongolia; [l]Department of Geography, The University of Utah, Salt Lake City, UT 84112; [m]Northern Michigan University, Marquette, MI 49855; [n]Department of Biology, Georgia Southern University, Statesboro 30458, Georgia; [o]New Mexico Museum of Natural History and Science, Albuquerque, NM 87104; [p]Wildlife and Fisheries Biology Program, University of Vermont, Burlington, VT 05405; [q]Department of Biology, University of North Carolina at Greensboro, Greensboro, NC 27402; [r]Institute of Behavioral Science and Department of Anthropology, University of Colorado-Boulder, Boulder, CO 80309; [s]Museum of Natural History, University of Colorado-Boulder, Boulder, CO 80309; [t]Department of Ecology and Evolutionary Biology, University of Colorado-Boulder, Boulder, CO 80309; [u]Department of Geological Sciences, University of Colorado Boulder, Boulder, CO 80309; [v]Department of Anthropology, University of Colorado-Boulder, Boulder, CO 80309; and [w]Biology Department and Museum of Southwestern Biology, University of New Mexico, MSC03 2020, Albuquerque, NM 87131

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[1]To whom correspondence may be addressed. Email: william.taylor@colorado.edu.

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retention of qualified staff (12). The peril of these issues is illustrated by the recent proposal to close the herbarium at Duke University, the largest plant repository in the southeastern United States (2). When such a facility closes, collections may be lost or transferred to distant repositories, reducing access to specimens for those asking locally relevant scientific questions, and local researchers asking questions of global significance (12). Perhaps most importantly, the loss of collections infrastructure and expertise also represents the loss of crucial opportunities for training and specimen-based education (13). Such opportunities are necessary to cultivate future generations of scientists capable of tackling ambitious questions that scale across time, space, taxonomic domains, and focus on biodiversity, evolution, and/or long-term human–environmental interactions; questions that often require natural history objects and associated metadata to answer.

Importantly, collections infrastructure is unevenly distributed across the globe. In some of the most ecologically and culturally significant regions of the world, the facilities and financial commitments necessary to collect, curate, or interpret specimens remain minimally allocated, leaving valuable materials at immediate risk of loss and limiting capacity for pursuing critical biodiversity discovery and surveillance programs (14, 15). The lack of locally anchored natural history infrastructure in the developing world and the Global South (16) represents a failure of the colonial scientific system, leaving many regions without the tools, training, or datasets needed to understand changing local landscapes and navigate contemporary biological problems. Here, we explore the scope of these issues using a detailed case study from the nation of Mongolia.

The Promise of Mongolian Museum Collections

With a population of just under 3.4 million and situated between two superpowers (the Russian Federation and People's Republic of China) in the heart of Asia, Mongolia highlights these unique challenges. Defined largely by the geography of the high, arid, and grassy Mongolian Plateau, Mongolia's people, plants, fungi, animals, and microorganisms have had a tremendous yet incompletely characterized impact on organismal evolution and the broad trajectory of human history. This region offers perhaps the most significant global window into Mesozoic paleontology (17) and may in fact be an origination site for placental mammals (18, 19). The region also likely played a key role in the initial dispersal of early humans into East Asia, and recent discoveries indicate that it was a locus of interactions among various early hominins, including *Homo sapiens*, Neanderthals, and Denisovans (20–22). Later in human history, Mongolia was a likely vector for the initial dispersal of domestic livestock such as sheep, goat, cattle, and horse into eastern reaches of the Asian continent (23–25). Over the most recent three millennia, pastoral empires from the region rose to the position of global superpowers, including the Mongol Empire, which formed the largest contiguous land empire in human history. These states centered Mongolian capitals as focal points for the exchange of people, goods, culture, and ideas (26). Pastoral polities drew together plants and animals from different areas of Eurasia (27, 28), integrated previously disparate human populations (29, 30), and played a crucial role in formalized trade and communication links across Eurasia via such means as the Mongol postal relay (31) and the Silk Road trade routes (32).

Continuing to piece together these historical events depends on Mongolian museum collections, which now are playing a dual role in understanding biodiversity response to various global change drivers. Many steppe mammals are hypothesized as pathogen reservoirs, such as the causative agents of brucellosis (*Brucella abortus*), foot-and-mouth disease (FMD virus), and plague (*Yersinia pestis*) (33–35), a disease that profoundly shaped Eurasian and African prehistory and continues to pose significant human and wildlife threats today. Mongolia is a major junction for migratory birds such as ducks, swans, shelducks, and gulls that transmit highly pathogenic avian influenza viruses (H5N1, H3N8) between breeding sites in Mongolia and wintering grounds in other Asian countries (36). Natural history collections could enable examination of ancient or contemporary pathogen reservoirs within the region, helping to understand why these zoonoses emerged into human populations and caused recurrent devastating epidemics, and elucidating the relationships between human–animal interactions, disease emergence, and prediction and control efforts in present-day populations. Mongolia is also experiencing more rapid rates of climate change than the world average (37), threatening the traditional livelihood of steppe herders (38, 39), while also offering an important opportunity to investigate what changes in biodiversity, environment, and society the future might hold for the rest of the world (40–45).

Today, Mongolia continues to be a major crossroads for humanity, with future transformations of natural environments ensured as a consequence of China's massive and ever-changing Belt and Road Initiative (46). However, a lack of long-term biodiversity sampling and biorepository infrastructure throughout Mongolia has and will continue to stymie efforts to monitor and mitigate the large-scale changes from this immense international development initiative. Natural history collections, when built to represent systematic sampling of natural communities over time and space, are among our best tools to assess anthropogenic impact in the dynamic world we live in today (9, 47). Cultural and anthropological collections, while often underappreciated, are critical tools for understanding processes like globalization, climate change, infectious disease emergence, and extinction (48, 49).

Mongolian museums house a wealth of critically important scientific materials, but many struggle with inadequate collections housing, and few are accessible to researchers or the public either physically or digitally. Major animal and plant collections, including vertebrate, invertebrate, and fungi collections are stored in museums at the National University of Mongolia, Mongolian Academy of Sciences, Natural History Museum, and in provincial museums. Based on our informal survey of collections data for Mongolian repositories available on the web, the Natural History Museum of Mongolia houses approximately 13,000 specimens, with 90 percent classified as biological, 5.3 percent as geological, and 4.1 percent paleontological (50). More than 3,300 specimens are prepared for exhibition, but about one-fifth of these are displayed in temporary housing. Mongolia also has two internationally indexed herbaria. The herbarium of National University of Mongolia (Index Herbariorum code: UBU) is maintained by the National

University of Mongolia and stores ~71,000 plant specimens, and the herbarium maintained by the Botanic Garden and Research Institute of the Mongolian Academy of Sciences (index code: UBA) houses over 128,000 specimens representing plants and other organisms (e.g., algae, fungi, lichens, etc.) (51). These museums struggle to expand their collections, but both facilities are collaborating with minimal funding on digitization initiatives. For zoology, the National University of Mongolia (NUM) houses about 300,000 invertebrate specimens and 3,000 vertebrate specimens, along with a small museum displaying around 750 animal specimens. The collections of the Institute of Biology of the Mongolian Academy of Sciences cares for over 4,100 specimens representing and documenting 115 species of mammals, and about 1,400 fish specimens including nearly all species that occur in Mongolia. The same institute houses about 100,000 specimens of insects including type specimens of over 3,000 species, and over 8,000 pure cultures of microorganisms including fungi, yeasts, actinomycetes, chromista, bacteria, and archaea. The NUM microorganism collection maintains pure cultures of 115 species of yeasts and 26 species of bacteria, but this represents a small fraction of the rich biodiversity of understudied beneficial and probiotic microbes currently under cultivation by Mongolia's nomadic pastoralists.

Museum Infrastructure, Training, and Accessibility in Mongolia

Despite the existence of these important, globally unique collections (Fig. 1 *A* and *B*) and the outsized role of the region in the evolving human story, crumbling infrastructure severely inhibits the safeguarding or study of these materials. Since the withdrawal of a formal Soviet presence in the 1990s, the country's museums and research facilities have suffered from

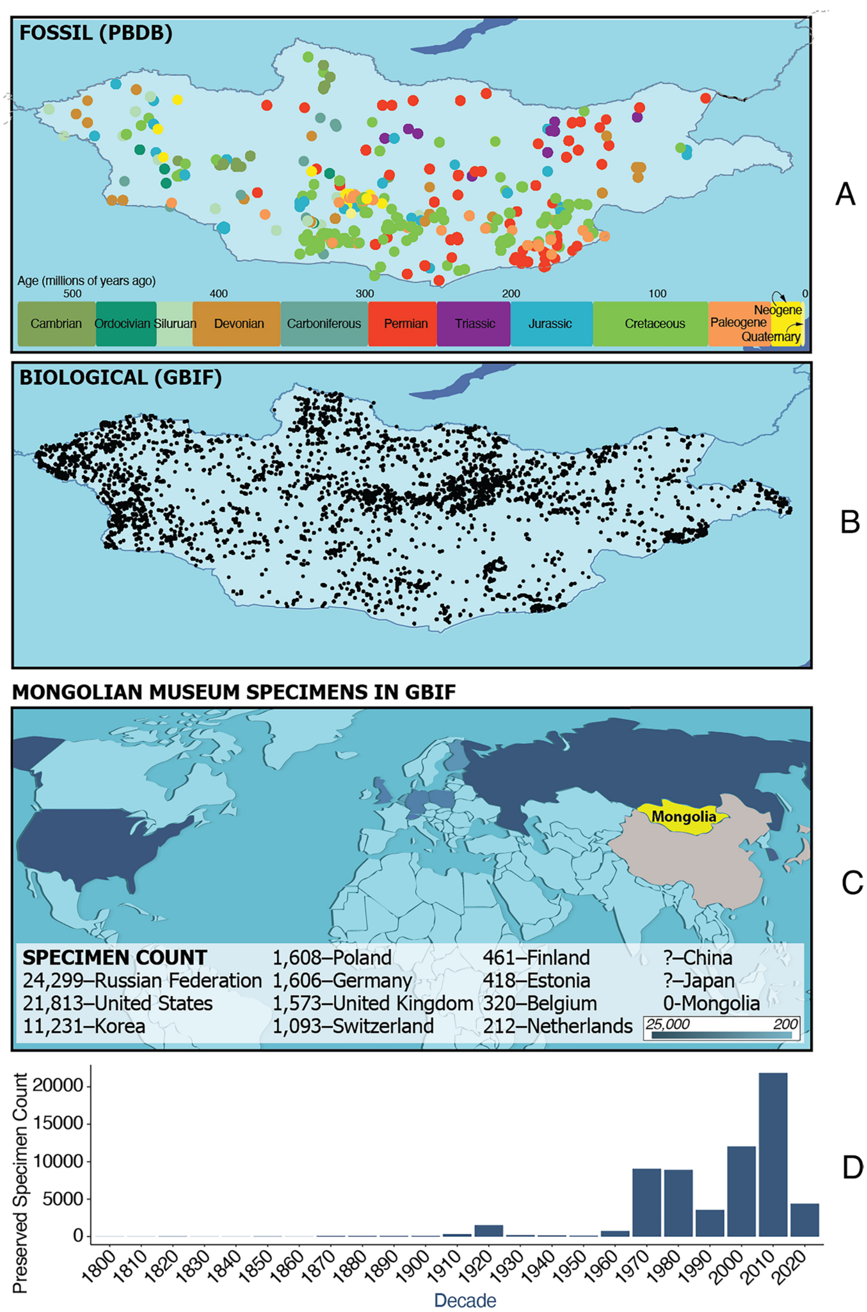

Fig. 1. (*A*) (*Top*) Geographic points of origin for Mongolian fossil specimens in PBDB (The Paleobiology DataBase), by geologic era. (*B*) (second from *Top*) Geographic points of origin for Mongolian biological specimens in GBIF (Global Biodiversity Information Facility). (*C*) (third from *Top*) Mongolian museum specimens digitized in GBIF, by country of curation. (*D*) (*Bottom*) Mongolian occurrence records in GBIF, by decade.

unrelenting financial drought, with many institutions struggling to remain viable. Museum infrastructure is heavily dependent on funding from foreign collaborations to conduct basic research, but foreign projects typically budget only for field and data generation expenses and not long-term curation, storage, or collections infrastructure; in fact, investment in local infrastructure and capacity building is explicitly prohibited by many foreign granting agencies. In 2013, Mongolia's Museum of Natural History shuttered its doors and was not reopened, with the building finally torn down in early 2019 for the construction of a new history museum. Although another facility (formerly the Central Dinosaur Museum) has now been given the Natural History moniker, the reference collections and research space that once housed some of the world's most important biological materials have not yet been replaced, with many collections still lingering in storage with precarious and limited accessibility. For microbes, heritage microbial ferments are being lost at an alarming rate due to climate instability, even as their medical and economic potential is only just now becoming apparent.

The cost of these missteps is dire. Within Mongolia, almost no comparative skeletal collections are available to conduct faunal identifications or comparisons. As a result, even basic analytical tasks, like morphological identification, may be unreliable—producing miscalculations that can be systemic and consequential to key scientific narratives (52). For example, while archaeological marmot (*Marmota* spp.) remains are crucial to understanding the deep history of the Eurasian plague (e.g., using ancient DNA techniques), few such specimens have been identified or retained in Mongolian museum collections. Due to the lack of facilities, biological or zooarchaeological materials are often discarded, poorly curated and unavailable, or exported to overseas collections. From publicly available information, for example, the Martin Luther University in Halle-Wittenberg, Germany, alone boasts maintaining one of the largest Mongolian vertebrate collections in the world (53) and their collection of Mongolian plants (HAL Herbarium) totals approximately 12,500 specimens comprising 1,698 species and subspecies (54). Two of the other largest collections of Mongolian plants in Germany are at the Plant Genetics Institute in Gaterslebem (GAT Herbarium) and Herbarium of the University of Greifswald (GFW), housing 10,500 and 5,000 specimens from the country, respectively (55). These three herbarium collections alone contain more than double the total amount of specimens curated at the Natural History Museum of Mongolia.

Although overseas curation does help ensure viability of some natural history specimens, the absence of comparable resources in Mongolia risks perpetuating scientific colonialism (Fig. 1*C*), eventually limiting access for both foreign and domestic Mongolian scholars (56). Travel costs and visa requirements are prohibitive barriers to Mongolian scientists studying their own natural and cultural heritage, and perhaps more significantly, Mongolian students find few opportunities for in-country training and career development. In digitized collections, although repository data demonstrate the growing importance of Mongolian collections to the international scientific community, almost none of Mongolia's domestic collections have been digitized (Fig. 1 *C* and *D*).

Meanwhile, many specimens are subject to widespread looting and illicit trade at a scale that is difficult to quantify. In September of 2024, Mongolia requested a Memorandum of Understanding with the United States Bureau of Educational and Cultural Affairs, seeking "protection of its cultural objects including archaeological material" for import restrictions (57), and earlier this same year a high-profile crackdown on illicit trade in paleontological specimens resulted in the return of a *Tarbosaurus* skull purchased at auction by the celebrity Nicholas Cage (58).

Microbial heritage management has not fared better. Inadequate funding for culture collection and maintenance has resulted in a scenario in which Mongolia, a country with a veritable wealth of probiotic culinary microbes, imports nearly all of the microbial starter cultures for its commercial food and beverage production. Even scientific papers themselves in Mongolia are at risk, with few Mongolian language journals stored in stable digital archives or integrated with international scholarship repositories. All of this contributes to a global asymmetry of natural history knowledge that imperils scientific research and collaboration and which is too common in the developing world (59).

Toward a Solution

We call upon the international scientific community to take urgent steps (Fig. 2) to develop a sustained plan of action to restore and build natural history infrastructure and human capacity in Mongolia, as well as in other parts of the

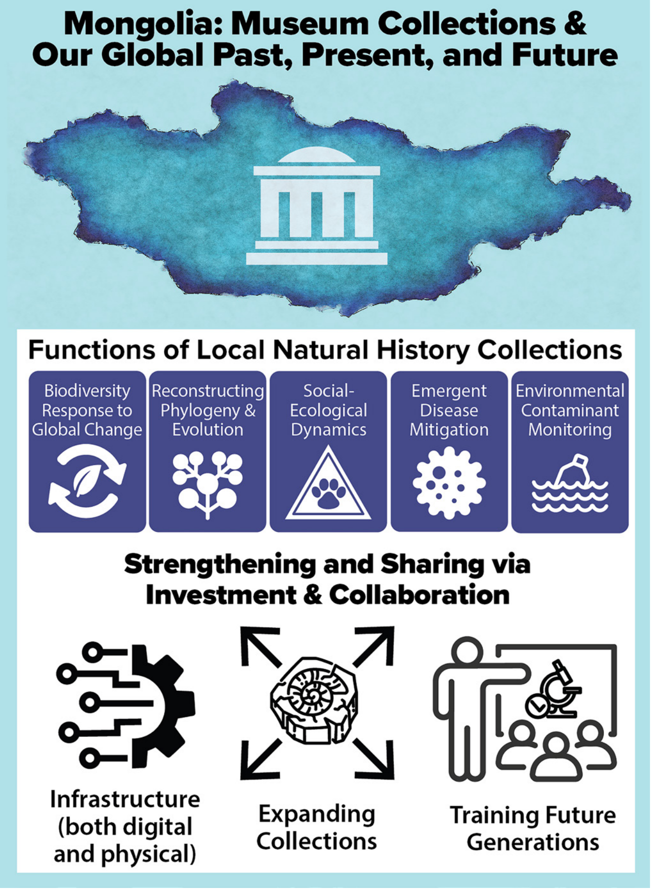

Fig. 2. The impact of Mongolian collections, and solutions for realizing their potential.

developing world, in line with the Access and Benefit-Sharing principles called for in international agreements such as the Nagoya Protocol of the Convention on Biological Diversity (60).

In many ways, the global scientific community cannot afford not to correct these gaps in the museum record—a recent quantification from the GBIF suggested that for every pound spent on this kind of shared infrastructure, users received a threefold direct benefit, and a 12-fold return in social benefits, from time and infrastructure savings to expanded research impact in everything from industry to policy (61). To address the issues of infrastructure, sample collection/curation, and training, we recommend strengthening infrastructure (both digital and physical), expanding collections, and improving training opportunities to build human capacity in field collection, curation, and specimen-based research. Improving infrastructure will likely require collaborative design and action from foreign partners, as well as government commitments and funding for facilities from international funding agencies, including those connected with American government sources, such as USAID's PEER program and others such as the Ambassador's Fund for Cultural Preservation. Even small or preliminary steps, such as building a stable digital repository for existing specimen data and scholarship for Mongolian institutions in partnership with American organizations in position to do so, will help build momentum toward sustained domestic capacity.

Improving sample collection for Mongolian repositories will entail building in-country capacity, through participation of local community members in fieldwork, university training of young professionals, and larger collections initiatives (62). International projects should seek out funders who permit investment in local infrastructure and find ways to allocate significant funds from every project towards training, collections, and curation. At the same time, institutions should require collections-producing projects to include a plan for generating local collections, or sample transfer agreements that require specimens to be shared or returned. Finally, training can be improved not only through investments in higher education but also by genuine involvement of Mongolian scientists, especially early-career scholars, in project research design and implementation, as well as expanding partnerships with international institutions through mutual exchange programs, and externally funded programs (12) such as USAID's PEER.

In a time of rapid environmental change, the case study of Mongolia highlights a set of global challenges in building fundamental science infrastructure, developing capacity, and creating more equitable access to locally anchored collections across the world. These challenges are manifest from colonial legacy across the Global South to even otherwise well-funded institutions in Europe and North America. Establishment of secure, domestic repositories for natural history materials with trained staff and a stable budget will stimulate local data collection and investment in laboratory resources and encourage the repatriation of biological and cultural heritage that is currently curated beyond Mongolia's borders. Strengthening local capacity through expanded support and funding at the international, state, and local levels—both in Mongolia and around the world, from the United States and Europe to the Global South—will improve collective ability to recognize, trace, and respond to global crises, including infectious disease outbreaks, and to contextualize both modern and ancient biological changes at deeper timescales. Healthy museums are natural centers of training for generations of homegrown scientists who are empowered and capable of leading efforts to document, study, and preserve the biological and cultural heritage of their community and their nation, ultimately serving the interests of all humanity.

Data, Materials, and Software Availability. All study data are included in the main text.

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